

Systematic study of high- p_T hadron and photon production with the PHENIX experiment

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Abstract.

The suppression of hadrons with large transverse momentum (p_T) in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV compared to a binary scaled p+p reference is one of the major discoveries at RHIC. To understand the nature of this suppression PHENIX has performed detailed studies of the energy and system-size dependence of the suppression pattern, including the first RHIC measurement near SPS energies. An additional source of information is provided by direct photons. Since they escape the medium basically unaffected they can provide a high p_T baseline for hard-scattering processes.

An overview of hadron production at high p_T in different colliding systems and at energies from $\sqrt{s_{NN}} = 22.4 - 200$ GeV will be given. In addition, the latest direct photon measurements by the PHENIX experiment shall be discussed.

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1. Introduction

One of the primary goals of the PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory is to study strongly interacting matter under extreme conditions. In particular the creation of a new state of matter, the Quark-Gluon Plasma (QGP) which is expected to form when energy densities above $\epsilon_0 \approx 1$ GeV/fm³ are attained in the collision.

One proposed signature of this new phase is the suppression of hadrons with large transverse momentum (p_T) compared to the expectation from scaled p+p reactions [1, 2]. The production of these particles is dominated by the scattering of partons with large momentum transfer Q^2 ($\propto p_T^2$), so-called *hard* scattering, and their subsequent fragmentation into observable particles in *jets* along the original parton direction.

The first step to quantify medium effects on particle production is to compare single particle spectra in heavy ion collisions to the expectation for the QCD vacuum. This is usually done by the nuclear modification factor R_{AA} , which compares the particle production in $A+A$ collisions to elementary p+p collisions scaled by a geometrical factor, the nuclear overlap function T_{AA} :

$$R_{AA} = \frac{d^2 N_{AA}/dydp_T}{T_{AA} \cdot d^2 \sigma_{pp}/dydp_T}. \quad (1)$$

T_{AA} accounts for the increased number of nucleons in the incoming A -nuclei and is related to the number of binary collisions N_{coll} by $T_{AA} \approx N_{coll}/\sigma_{inel}^{pp}$. In the absence of

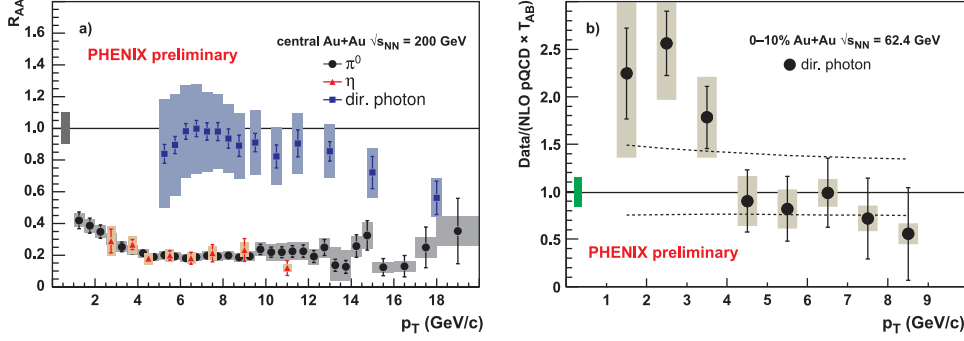


Figure 1. a) Nuclear modification factor for π^0 s, η s and direct photons in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. p_T uncorrelated uncertainties are given as error bars, correlated as boxes around the points. The normalization is shown by the box at unity. b) R_{AA} for direct photons in central Au+Au collisions at $\sqrt{s_{NN}} = 62.4$ GeV, uncertainties as in a), the shift with respect to unity when using different scales ($\mu = 0.5, 2.0 p_T$) in the pQCD reference calculation is given by the dashed lines.

any medium effects and at sufficiently high p_T , where hard scattering is the dominant source of particle production R_{AA} should be unity, any deviation from unity indicating the influence of the medium.

Indeed, already the first hadron measurements in Au+Au reactions at RHIC showed a hadron yield suppressed up to a factor of five in central collisions [3, 4, 5]. This suppression can be explained by the energy loss of hard scattered partons via induced gluon bremsstrahlung in a medium with high color density. However, with the first hadron measurements it was not possible to distinguish experimentally between final state effects, e.g. parton energy loss, and the effects of cold nuclear matter. These initial state effects can enhance or suppress the particle production compared to p+p and involve e.g. multiple soft scattering of incoming partons or nucleons (Cronin effect), or a modification of the parton distribution function in a nucleus (shadowing, anti-shadowing or gluon-saturation).

Initial state effects have subsequently been ruled out as a source of the observed suppression by two key results in d+Au and Au+Au at $\sqrt{s_{NN}} = 200$ GeV:

- Charged hadrons and neutral pions are not suppressed in d+Au collisions (cold nuclear matter) [6].
- The nuclear modification factor for direct photons at high p_T is consistent with unity [7].

The latter provides the in-situ control for parton energy loss and for the assumption of a geometrical scaling for hard scattering, since direct photons are also produced in initial hard scattering but are not affected by the strong interaction. They can traverse the plasma basically unaltered and at high p_T the direct photon yield should directly reflect the initial state of quarks and gluons in the nucleus. Going to lower p_T the measurement of direct photons in A+A collisions can provide further information on the medium, since other photon sources become important. These involve e.g. the interaction between hard scattered and thermal partons, photon bremsstrahlung in the QGP and thermal radiation.

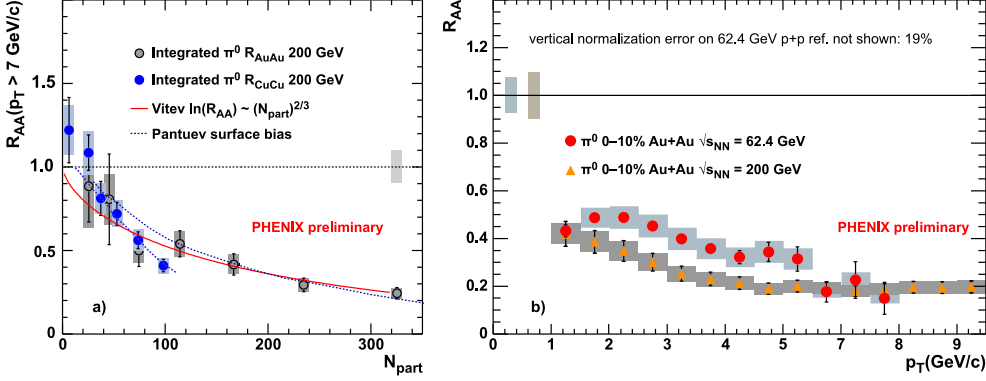


Figure 2. a) Integrated nuclear modification factor for Au+Au and Cu+Cu collisions compared to a scaling with $N_{part}^{2/3}$ [10] and a model with surface/volume effects [11]. b) Nuclear modification factor in central Au+Au collisions at $\sqrt{s_{NN}} = 200$ and 62.4 GeV. Uncertainties as described in Figure 1, the 19% normalization error of the p+p data at 62.4 GeV is not shown.

Since the first observation of suppressed particle production the study of high p_T particles via the nuclear modification factor has been a major tool for studying the dense nuclear matter. In fact, the observations at RHIC triggered also an extensive search for similar effects in data taken at the CERN/SPS (see e.g. [8, 9]).

In this paper we will concentrate on the most recent measurements of identified particles by the PHENIX experiment at high p_T for different colliding systems and energies. The main information in this region is provided by the measurement of neutral mesons (π^0, η) and direct photons, this allows to study different mesons from parton fragmentation and direct photons produced in early hard scatterings.

2. Data analysis and results

The data presented here has been collected by the PHENIX experiment during three different RHIC runs and spans the following collision species and energies:

RHIC run	Species	$\sqrt{s_{NN}}$ (GeV)
4	Au+Au	200, 62.4
5	Cu+Cu p+p	200, 62.4, 22.4 200
6	p+p	200, 62.4

The choice of copper as colliding system has been motivated by the fact, that the suppression in Au+Au sets in at a centrality corresponding to approximately 50 – 100 participating nucleons (N_{part}), see Figure 2a). Copper allows to study this range in more detail at a more spherical collision geometry.

All measurements have been performed using the electromagnetic calorimeter EMCal. It is the outermost detector of the PHENIX central arm and provides a solid angle coverage of $-0.35 < \eta < 0.35$ and $\Delta\phi = \pi$. The π^0 and η mesons are reconstructed via their two-photon decay with an invariant mass analysis of photon pairs. The combinatorial background is determined by a *mixed event* technique, where photon pairs from different events are combined to form the uncorrelated background.

The raw spectra are corrected for the geometrical acceptance and for reconstruction efficiency losses.

Direct photons are by definition all photons not originating from radiative decays. The direct photons can thus be determined by comparing the inclusive photon spectrum, obtained after subtraction of charged particle and neutral hadron contributions to the EMCal cluster spectrum and correction for efficiency and acceptance losses, to the expectation from decay photons, which are mainly originating from $\pi^0, \eta \rightarrow \gamma\gamma$. Any excess above this expectation is considered as a direct photon signal [7].

3. Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

The factor of 15 more sampled events in Au+Au collisions during RHIC's fourth run compared to the first data taking at design energy allows to study the production of neutral pions up to $p_T = 20$ GeV/c. A similar improvement in the p_T range was also reached in the p+p reference data. The resulting nuclear modification factor shown in Figure 1a) is basically flat up to the highest p_T .

The fact that neutral pions and η s show the same amount of suppression indicates that the jet-quenching mechanism does not depend on the mass of the (light-quark) meson. This is expected when the suppression only depends on the energy loss of the parent quark and not on the leading hadron itself, which is produced in a universal fragmentation process.

The direct photon result confirms the measurement from [7], a nuclear modification factor of unity up to $p_T = 14$ GeV/c, which can be attributed to the insensitivity of hard scattered photons to the produced medium. However, at higher p_T a decrease of the direct photon yield becomes apparent. One may speculate on the influence of photons from parton fragmentation, which would be suppressed in Au+Au, but this effect should rather decrease with p_T . A simpler explanation can be given by the influence of protons and neutrons in the nucleus.

When studying strong processes the difference between n and p is basically negligible. This is not the case in the production of direct photons, where the scattering (e.g. $qg \rightarrow q\gamma$) involves an electromagnetic vertex. However, the normalization to p+p in the nuclear modification factor does not account for the fact that already the elementary processes p+p, p+n, and n+n are different when the valence quark distributions become important at a certain probed momentum fraction $x_T \approx p_T/\sqrt{s_{NN}}$. This trivial isospin effect can be estimated via a pQCD calculation of the elementary processes to be of the order of 15% for $x_T = 0.1$ [12]. However the interplay between different effects, isospin, modified structure function and the influence of fragmentation photons should also be considered (see e.g. [13]).

An experimental handle on the isospin effect is given by the study of direct photons at lower collision energy, which allows to study the effect at the same x_T but lower p_T . The first results on direct photon production at $\sqrt{s_{NN}} = 62.4$ GeV shown in Figure 1b) indicate a similar suppression at the expected lower p_T , but the statistical uncertainties as well as the missing p+p reference at this energy prevent any firm conclusions at the moment.

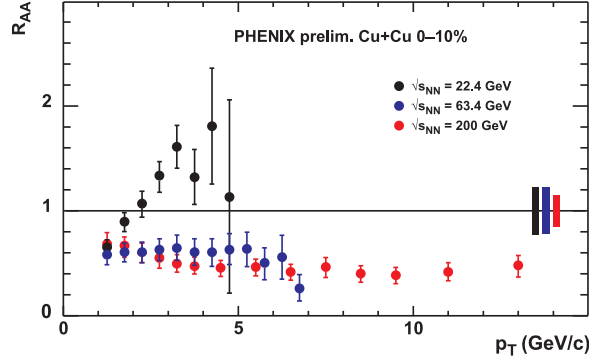


Figure 3. Energy dependence of the nuclear modification factor in central Cu+Cu collisions. The combined normalization error due to the uncertainty in T_{AA} and the scale uncertainty of the p+p reference is indicated by the error boxes around unity, systematic and statistical uncertainties are summed in quadrature and given by the error bars.

4. System size and energy dependence

The study of different system sizes is motivated by the fact that smaller systems allow a better discrimination for smaller values of N_{part} and hence at a smaller energy density. E.g. Cu+Cu ($A = 63$) collisions allow to sample the N_{part} -range of peripheral Au+Au ($A = 197$) collisions. In addition, it provides an insight into the influence of the collision geometry, since at the same N_{part} the overlap region is more spherical for smaller systems.

It is found that the p_T dependence of the nuclear modification factor at the same N_{part} is very similar for Au+Au and Cu+Cu collisions (not shown, see e.g. [14]). This is also seen in the centrality dependence of the integrated nuclear modification factor for Cu+Cu and Au+Au in Figure 2a). R_{AA} follows approximately a scaling with $\ln(N_{\text{part}}^{2/3})$, which is inspired by the volume dependence of the energy density [10]. However, the slightly different slopes can be better explained when taking into account surface effects as e.g. in [11], where it is assumed that only jets originating from a certain depth below the surface can be observed.

A important constrained to any description of the in-medium energy loss is provided by the measurement of the energy dependence. Since at different energies not only the energy density varies but also the influence of initial state effects, such as the Cronin enhancement and shadowing, changes as well as the slope of the spectra.

For the determination of the nuclear modification factor the knowledge of the baseline p+p reference is crucial. This is nicely illustrated by the R_{AA} for central Au+Au at $\sqrt{s_{NN}} = 62.4$ GeV shown in Figure 1b) and constructed with the measured PHENIX p+p reference. Compared to previous comparisons which only employed a reference fit to ISR data, it shows that already at 62.4 GeV the suppression in R_{AA} is more than a factor of two and follows a similar p_T dependence as the data at $\sqrt{s_{NN}} = 200$ GeV.

This behavior is also seen in Cu+Cu collisions at $\sqrt{s_{NN}} = 200$ GeV and $\sqrt{s_{NN}} = 62.4$ GeV shown in Figure 3, again both energies show a very similar p_T dependence and magnitude of the nuclear modification factor. However, one also has

to consider that the slope of the scattered partons at $\sqrt{s_{NN}} = 62.4$ GeV is steeper compared to 200 GeV, so an energy loss $\Delta E/E$ is more pronounced. Hence, the same R_{AA} at different energies is not tantamount to the same parton energy loss.

The nuclear modification factor close to CERN/SPS energies has been measured for the first time at RHIC by the PHENIX experiment in Cu+Cu collisions at $\sqrt{s_{NN}} = 22.4$ GeV. Though the measurement of p+p reactions at this energy within PHENIX is still missing, the wealth of data for p+p $\rightarrow \pi^0/\pi^\pm + X$ in the range of $\sqrt{s_{NN}} = 21.7 - 23$ GeV allows to construct a reference with a systematic uncertainty of $\approx 20\%$. The resulting R_{AA} is also shown in Figure 3 and exhibits no suppression, instead it indicates an enhancement. To understand whether parton energy loss is present but compensated by Cronin enhancement the measurement of Au+Au collisions is needed to reach higher energy densities, as well a solid p+p reference at the same energy.

5. Conclusion

We have shown a systematic study of neutral meson and direct photon production at high p_T measured with the PHENIX experiment, based on the nuclear modification factor for different particle species, colliding systems and center-of-mass energies.

The nuclear modification factor in central Au+Au at top RHIC energies is flat up to $p_T = 20$ GeV/c and shows a similar suppression for π^0 s and η s while for direct photons no suppression is observed over a wide p_T range. The deficit of direct photons at the highest p_T may be due to an isospin effect, but the interplay between different nuclear and medium effects needs to be investigated further.

The nuclear modification factor is similar in the two colliding systems Cu+Cu and Au+Au at a similar N_{part} , with indication that geometry effects need to be considered. We have also shown the first study of the energy dependence of R_{AA} from $\sqrt{s_{NN}} \approx 20 - 200$ GeV, within the same experiment. It shows that suppression already is a dominating effect at $\sqrt{s_{NN}} = 62.4$ GeV, while close to CERN/SPS energies an enhancement is observed.

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